Dynamic Strength Correlations

Sudhakar L. Rajulu[1], Ph.D. and L. Javier Gonzalez[2], Ph.D.
[1]Baylor College of Medicine-NASA/NSBRI, [2] SpaceHab-Johnson Engineering
Anthropometry and Biomechanics Facility
NASA-Johnson Space Center
2101 NASA Rd 1, SF3
Houston, Texas 77058

ABSTRACT

Computer simulations of actual human-work interface interactions, once developed, are less expensive and easier to modify than conducting the actual tests. Due to the successful applications of these virtual human models, efforts are under way to develop such models for generic applications. Unfortunately, there are important issues that need to be addressed before developing such generic models. The purpose of this paper is to address these issues by discussing the analysis of a large sample of dynamic strength of multiple joints. A poor correlation was observed between joint strengths in subjects who fell between the 25th and 75th percentile range. Virtual human modeling may thus be most accurate in predicting an individual's strength capabilities when he or she is either clearly weak or clearly strong.

INTRODUCTION

Researchers have long been attempting to show that it is possible to conduct task-oriented biomechanical simulation that incorporates strength, reach, and postural data [1, 2, 4]. Computer simulations of actual human physical performance, once developed, are less expensive and easier to modify than conducting actual testing and evaluation [14]. In addition, they do not require elaborate set-ups of the actual work interface or the work environment, some of which, such as microgravity, are very difficult and costly to reproduce [19]. Hence NASA, as well as many universities and commercial entities, are interested in advancing the technology of developing virtual human models [3, 7, 4].

One major advantage of a virtual human model is that it can predict the joint forces and moments while a person is performing a task in a free dynamic posture. Whether one is seeking to understand the causation of work-related injuries [16], the effects of joint surgery [9, 10], or the effects of modifications of an existing human-work interface [19, 11], one needs to know the dynamic posture of the whole body and the amount of forces and moments required at various joints to maintain that posture. At present, these joint-specific internal forces and moments are impossible to measure directly. Researchers have desired a means to quantify these joint forces and moments for a long time; the virtual models have the capability to fill that void.

Until now, virtual simulation models have been developed for very specific applications and have been valuable in their ability to assess a specific problem [18, 19, 11]. Due to these successful applications with excellent visual graphics presentation, there is now a growing interest to advance these models to use them generically for all applications of human-work interface design and evaluations [12,18, 15]. Unfortunately, these models still lack the ability to model and predict the specific capabilities of individuals drawn from a general population [5,15]. This is primarily due to the fact that current models use strength databases that were taken from a relatively small sample (~ 20) of the subject population [8, 11, 12]. Even if the models employ a large strength database, there are issues that have not been addressed adequately yet.

For example, there have been no reports that address the following issues:

a) How related are the strength capabilities of different joints within the same individual?
b) How shall a person's strength profile be characterized– in a general sense or in a specific sense?
c) Is it possible to predict an individual's capabilities during a generic task based upon strength data gathered from a small pool of subjects participating in a specifically controlled study?

The purpose of this paper is to address these issues.

OBJECTIVES

The objective of this presentation is to present preliminary results of our own analyses of a large sample of isolated joint strength data, which we have been gathering at NASA as part of our astronaut selection process. More specifically, this paper is aimed at documenting the challenges in dealing with those aspects of strength data that may be helpful for model developers and users. Additionally, we would like to point out and quantify certain pitfalls that lie ahead for the developers and users who are interested in percentile-based anthropometric and strength characteristics.

METHODOLOGY

Subjects

The dynamic isolated joint strengths of back, shoulder, elbow, and knee joints were taken from 457 astronaut candidate applicants. As part of their selection process, these applicants were required to perform specific strength tests. Table 1 lists the breakdown of subject classification.

Table 1. Number of Subjects per Joint Tested

Gender	Back	Knee	Elbow	Shoulder
Females	65	94	94	93
Males	201	362	363	363
Total	266	456	457	456

The back strength testing had to be discontinued after intermittent equipment failure of the back strength attachment of the testing apparatus, hence the reason for smaller number of subjects for back strength.

Apparatus

The strength testing was done using a LIDO isokinetic dynamometer (Loredan Biomedical, Inc., West Sacramento, CA). This isokinetic dynamometer is similar to an exercise device, with the exception that it not only controls joint torque but also monitors and collects joint torque data at user-specified test conditions. One unique feature of the LIDO dynamometer is that it allows for gravity compensation, which removes the effect of body segment weights and the weights of the dynamometer's attachment from the measured torque. Hence, only the subject's actual effort is registered.

Experimental Design

Each subject performed maximally the shoulder flexion/extension, the elbow flexion/extension, the knee flexion/extension, and the back flexion/extension. The order of presentation of the trials was shoulder, elbow, (back), and knee; or, knee, (back), elbow, and shoulder. The velocity of motion was set at 1.05 red/sec (60 deg/sec). The subjects were asked to exert their voluntary maximal effort against the dynamometer and maintain the effort throughout the entire range of motion. Table 2 lists the independent variables and the levels of each variable. The dependent measure is the maximal voluntary torque.

Table 2. List of Independent Variables

Variable	Levels	Description
Gender	2	Male, Female
Joint	4	Elbow, Shoulder, Back, Knee
Direction	2	Flexion/Extension

Experimental Procedure

Depending upon the joint to be tested, the appropriate LIDO attachment for isolating the joint was attached to the dynamometer. The LIDO dynamometer and the workbench were then adjusted to accommodate the subject, who was either seated or otherwise positioned properly for the specific joint testing. Proper procedures, as prescribed by the equipment manual, were employed to align the dynamometer and its attachment. Familiarization sessions and trial runs were given both before and during the actual testing. The subject was instructed to move the LIDO attachment back and forth three times while applying maximal exertions throughout the range of motion (ROM). The subject set the ROM during the familiarization sessions. After completion of one trial of 3 repetitions, the variation between the three repetitions was computed to determine whether or not to repeat the trial. A variation of more than ten percent in torque from the three reps led to a repeat of the same joint testing before proceeding to the next joint. Rest breaks of 2-3 minutes were administered between trials to minimize fatigue effects.

Data Analysis and Treatment

Raw torque and angle data gathered from each subject were reduced to obtain the maximum torque in both directions (flexion/extension) for each repetition and averaged across the three repetitions to obtain the maximum torque for each joint. During analysis, both males and females were grouped together since we had only 93 female subjects as compared to 363 male subjects. In addition to the all-subject analysis, male and female subjects were analyzed separately to observe the gender differences in strength. For some test conditions, we had fewer subjects, as shown in Table 1, due to an error in some of the subjects' raw data files.

RESULTS

Descriptive Statistics

Table 3 shows the basic statistical summary. It provides comprehensive statistics on the range of joint torque capacities of a relatively large population. In general, we see that both elbow and shoulder joints have much less strength than the back and knee joints. The back and the shoulder joints have more extension torque than flexion torque, whereas knee and elbow joints have more flexion than extension torque capability. The back joints also have almost twice the capability during extension than during flexion. Female strengths were about 50% to 60% of the males, depending upon the joint in question.

Table 3. Joint Torque Statistical Values for Female and Male Subject Groups

Statistics	*Female Subjects*							
	Back		Knee		Elbow		Shoulder	
	Flex	Ext	Flex	Ext	Flex	Ext	Flex	Ext
Maximum (N·m)	185	377	181	125	39	35	44	64
Minimum (N·m)	50	115	65	352	17	13	19	24
Average (N·m)	120	248	123	69	27	22	29	42
Standard Deviation (N·m)	25	58	25	16	5	5	5	9
	Male Subjects							
	Back		**Knee**		**Elbow**		**Shoulder**	
	Flex	**Ext**	**Flex**	**Ext**	**Flex**	**Ext**	**Flex**	**Ext**
Maximum (N·m)	331	597	319	183	87	70	81	141
Minimum (N·m)	79	186	87	60	28	22	31	40
Average (N·m)	186	389	201	114	55	42	55	84
Standard Deviation (N·m)	38	80	39	22	10	8	9	16

Simple Correlation Coefficients

Tables 4a and 4b show the correlation between various joint strengths. The correlation between the joint strengths reduced when subjects were separated into male and female groups. Even after a reduction in the correlation coefficients, the trend within the correlation matrix did not change across the three groups (all subjects, male, and female). The highest correlation was between the elbow and the shoulder joints and the lowest was between the back and the elbow joint. The coefficients remained the same, regardless of the direction of motion (flexion vs. extension).

Table 4a. Correlation Coefficients Between Joint Strengths (Extension)

All Subjects

Variable	Back (ext)	Elbow (ext)	Knee (ext)	Shoulder (ext)
Back (ext)	1	0.72	0.69	0.72
Elbow (ext)	0.72	1	0.74	0.91
Knee (ext)	0.69	0.74	1	0.75
Shoulder (ext)	0.72	0.91	0.75	1

Female Subjects

Variable	Back (ext)	Elbow (ext)	Knee (ext)	Shoulder (ext)
Back (ext)	1	0.48	0.56	0.60
Elbow (ext)	0.48	1	0.52	0.80
Knee (ext)	0.56	0.52	1	0.57
Shoulder (ext)	0.60	0.80	0.57	1

Male Subjects

Variable	Back (ext)	Elbow (ext)	Knee (ext)	Shoulder (ext)
Back (ext)	1	0.48	0.43	0.46
Elbow (ext)	0.48	1	0.52	0.81
Knee (ext)	0.43	0.52	1	0.51
Shoulder (ext)	0.46	0.81	0.51	1

Table 4b. Correlation Coefficients Between Joint Strengths (Flexion)

All Subjects

Variable	Back (flex)	Elbow (flex)	Knee (flex)	Shoulder (flex)
Back (flex)	1	0.75	0.72	0.74
Elbow (flex)	0.75	1	0.79	0.88
Knee (flex)	0.72	0.79	1	0.76
Shoulder (flex)	0.74	0.88	0.76	1

Female Subjects

Variable	Back (flex)	Elbow (flex)	Knee (flex)	Shoulder (flex)
Back (flex)	1	0.60	0.58	0.68
Elbow (flex)	0.60	1	0.68	0.75
Knee (flex)	0.58	0.68	1	0.62
Shoulder (flex)	0.68	0.75	0.62	1

Male Subjects

Variable	Back (flex)	Elbow (flex)	Knee (flex)	Shoulder (flex)
Back (flex)	1	0.50	0.50	0.47
Elbow (flex)	0.50	1	0.57	0.71
Knee (flex)	0.50	0.57	1	0.50
Shoulder (flex)	0.47	0.71	0.50	1

Table 4c contains the correlation between extension and flexion strengths of the four joints tested in this study. When the male and female subjects were combined into one group, all joints except the back joint exhibited a strong flexion-extension correlation. When they were tested separately, the correlation reduced as expected. Still, the trend remained the same: The elbow joint had the highest flexion-extension correlation and the back had the lowest.

Table 4c. Correlation Coefficients Between Flexion and Extension

Joint	All Subjects	Male Subjects	Female Subjects
Back	0.78	0.63	0.61
Elbow	0.91	0.79	0.86
Knee	0.86	0.77	0.72
Shoulder	0.88	0.71	0.74

Interrelationship Among Joint Strength Percentiles

Since the strength correlation between any two joints was not high for both the male and the female group, we were interested in determining whether the joint strengths would relate to each other differently if they were normalized. In addition, we were interested in identifying any percentile-based regions that may exhibit trends not captured by the analysis of correlation.

First, each person’s joint strengths were statistically compared across the subjects (one joint at a time) and the percentile values for each person’s four joint strengths were derived separately. For gender analysis, percentiles were calculated without pooling the subjects together. For the whole group analysis, male and female strengths were pooled together to convert the joint strength into percentile data. Next, each person’s joint strength percentiles, one joint’s strength at a time, were individually grouped into 4 bins (each bin corresponds to a quartile, namely 0-25, 26-50, 51-75, and 76-100 percentile). The selection of a 4-bin analysis is somewhat realistic in the sense of classifying a person as either belonging to the 1^{st}, 2^{nd}, 3^{rd}, and 4^{th} quartiles. We created a set of tables similar to 6a, 6b, and 6c, for each gender and for the whole group.

Table 6a. Bin Analysis of Back Strength Percentile in Comparison to the Elbow, Knee, and Shoulder Strength Percentiles

	Elbow % tiles				Knee % tiles				Shoulder % tiles			
Back % tiles	**0-25**	**25-50**	**50-75**	**75-100**	**0-25**	**25-50**	**50-75**	**75-100**	**0-25**	**25-50**	**50-75**	**75-100**
0-25	37	13	13	10	37	16	8	12	35	16	15	7
25-50	15	23	14	10	20	20	16	6	17	17	21	7
50-75	11	17	20	16	15	12	15	21	9	17	21	17
75-100	9	15	16	26	10	17	18	22	8	10	30	19

Table 6b. Bin Analysis of Knee Strength Percentile in Comparison to the Elbow and Shoulder Strength Percentiles

	Elbow % tiles				Shoulder % tiles			
Knee % tiles	**0-25**	**25-50**	**50-75**	**75-100**	**0-25**	**25-50**	**50-75**	**75-100**
0-25	88	24	3	1	89	18	8	2
25-50	14	44	34	18	9	42	48	11
50-75	4	26	37	31	3	19	49	26
75-100	3	20	36	72	2	20	42	67

Table 6c. Bin Analysis of Elbow Strength Percentile in Comparison to the Shoulder Strength Percentile

	Shoulder % tiles			
Elbow % tiles	**0-25**	**25-50**	**50-75**	**75-100**
0-25	92	17	0	0
25-50	10	57	44	3
50-75	0	24	70	18
75-100	0	2	33	86

We can see from Table 6a that it is very hard to make any assumption on what a person's lower limb's and upper limb's strength percentiles would be based on his or her back strength percentile. However, there appears to be a good interrelationship between the lower limb (knee) and the upper limb (elbow and shoulder) strength percentiles, at least in the top (76^{th} to100^{th}) and the bottom (0 to 25^{th}) quartiles (see Table 6b). In the mid-50 percentile range (25^{th} to 75^{th}), it was still quite difficult to discern any distinct patterns. Interestingly, the trend actually improved when the joint strength percentiles of the upper limbs were compared (see Table 6c). Once again, as in the case of the correlation of the strength percentiles among the knee, elbow, and the shoulder joints, there was an excellent correlation between the elbow and shoulder strength at both the top and bottom quartiles. Even in mid range, a considerably higher number of subjects shared the 2^{nd} and 3^{rd} quartiles for both elbow and shoulder joint strength percentiles.

Table 7 shows the overall percentage of subjects whose any two joint strength percentiles fell within the same bin (percentile range). For example, in Table 7a, only 36% of the subjects had back and knee joint strength percentiles that fell into the same bins. This clearly shows that, across the entire percentile ranges of two joint strengths, there was very little correlation between the back and knee joints. The same bin correlation did improve that involved knee, elbow, and shoulder joints only. The improvement in the bin correlation was marginal for males (see Table 7c), while the female group did have a marked improvement. Unfortunately, Table 7 shows that that there is too much variability rather than commonality between any two joint strengths of an individual.

Table 7. Percentage of Subjects With Joint Strength Percentiles in the Same Quartiles Between Any Two Joints

(a) All subjects combined together

Joint	Knee	Elbow	Shoulder
Back	36%	40%	35%
Knee		51%	54%
Elbow			67%

(b) Female subjects

Joint	Knee	Elbow	Shoulder
Back	35%	33%	42%
Knee		43%	44%
Elbow			56%

(c) Male subjects

Joint	Knee	Elbow	Shoulder
Back	44%	42%	39%
Knee		47%	40%
Elbow			49%

Figures 1, 2, and 3 show how the pattern of correlation changes across the bins within each possible joint-to-joint combination. In these figures, "B" refers to the back, "K" refers to the knee joint, "E" refers to the elbow joint, and "S" refers to the shoulder joint. In Figure 1, the first group of four columns represents the bin-to-bin correlation between the back and the knee joint strength percentiles. Within this group of vertical columns, the first column represents the percentage of subjects who were within the 0-25th percentile bin for the back who were also within the 0-25th percentile bin for the knee joint.

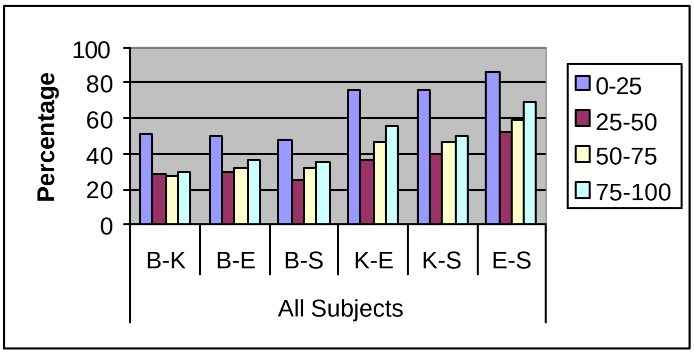

Figure 1. Bin analysis for all subjects combined as a group

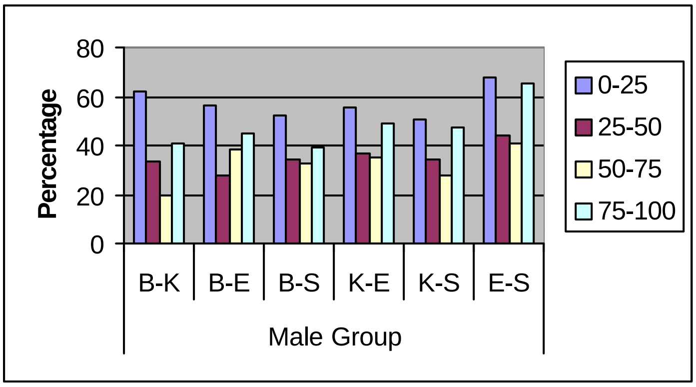

Figure 2. Bin analysis for male subject group

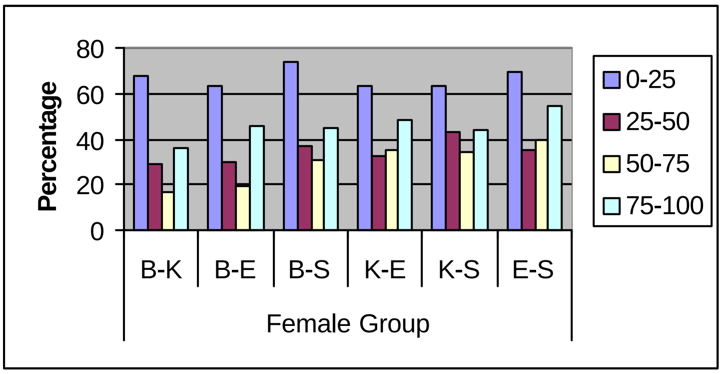

Figure 3. Bin analysis for female subject group

Surprisingly, these figures show that there is actually a good correlation between joint strengths for the following conditions:

a) For all male and female subjects whose strength percentiles were less than the 25^{th} percentile and
b) For all males whose knee, elbow, and shoulder joint strength percentiles were greater than the 75^{th} percentile

The poor overall bin correlation that was seen in Table 7, therefore, is mostly attributable to the lack of correlation within the subjects whose joint strengths fell between 25^{th} and 75^{th} percentiles. The study has thus identified a trend in correlation within the percentile range that was overlooked by the conventional correlation method.

DISCUSSION

The primary objective of this study was to report the findings from the analyses of a relatively large sample of multiple (isolated) dynamic joint strength data. Before publishing these data, we conducted an exhaustive literature search on dynamic strength studies. To date, there were virtually no published reports on how different joint strength capacities are related to each other within an individual. We also did not find reports on dynamic strengths that were based on a relatively large population. Hence, we are hopeful that the results from this study may provide new insights for researchers engaged in virtual human modeling as well as in occupational ergonomics.

Not all joints exhibited the same trend when we compared the exertion capability during flexion and extension. While back and shoulder joints had more exertion capability during extension, the knee joint had more flexion than extension capability. We also found that the back joint, followed by the knee joint, has more torque capability than the shoulder and the elbow joints. A possible biomechanical explanation may lie in the segment mass (back joint) and the involvement of large muscle groups (knee joint).

We found that the strength correlation became inflated when male and female subjects were pooled together. Regardless, the correlation trends remained relatively the same across all subject groups. The highest correlation was found between the shoulder and the elbow. The back joint had the lowest correlation with the rest of the joints we tested. We are not sure why the correlation is low for the back joint, except for the fact that we had a smaller sample of subjects tested for the back strength compared to the other joints. Overall, the analysis of correlation showed that all of an individual's joint strengths are not highly correlated. Similar results were also observed when joint strengths were normalized into percentile data. Only 30% to 50% of the sample population exhibited similar percentile-based bin correlation. These results indicate that an individual's strength capabilities have to be classified with specificity.

A few interesting trends also emerged when the percentile ranges were divided into 4 bins. First, the bin analysis showed that the poor overall correlation was mostly attributable to inconsistencies in joint strengths of individuals whose strengths fell between the 25th and 75th percentiles. This was evidenced by the fact that the bulk of the same bin correlation came from the bottom quartile (0-25th %le) followed by the top quartile (75th –100th %le). Roughly 60% of the subjects whose individual joint strengths were in the bottom quartile of a joint strength were also found to be in the bottom quartile of the other joints. In contrast, only about 28 to 40% of the subjects from the two mid-quartiles (25th -75th %le) were found to be in the same mid-quartiles of the other joints. Second, the percentage of subjects in the top quartile (75th-100th %le) who shared the same top quartile between the joints improved from 20% to 41%, suggesting that some joints tend to exhibit more correlations at the top quartile range. Therefore, it appears that there is a range-bound correlation between the four joints we tested. Both gender groups tend to exhibit a high correlation between joint strengths as long as they meet one of the following conditions:

a) The subjects are either clearly weak (0-25th %le) or clearly strong (75th-100th %le); or
b) The joints have a close association (elbow-shoulder) and are similar to each other (elbow-knee) functionally.

We also found some evidence that suggests that there may be a very good correlation in strength percentiles among joints within the upper limb or within the lower limb. According to our bin analysis, the elbow and shoulder joint strength percentiles had a much better correlation as compared to any other combination of joint strengths. More testing is, however, needed to verify this finding.

CONCLUSIONS

The isolated joint strengths are not correlated well with each other when they fall between 25th and 75th percentiles. However, there is a good correlation at the extreme ranges of the strength percentiles. Virtual human models that depend on strength data may work well for predicting the strength capabilities of a weak individual and possibly for a strong individual. Prediction from human models may not be accurate for those whose strengths fall in between the extremes. Poor correlation of joint strengths of a relatively large sample of subjects leads us also to believe that the human models that rely on strength data from a small sample may have poor predictive capabilities. We highly recommend the use of strength data from a large sample of subjects.

FUTURE WORK

We are proposing more analyses to further our understanding of the dynamic capacities of the human joints. We are working on refining the bin analysis to further understand the strength correlation between joint strengths that fall within the bottom and top quartiles. We are also investigating the feasibility of developing a composite human strength model as a means to profile human strength extremes (such as weak and strong). Finally, we are in the process of developing functional strength percentiles by using the isolated joint strength database.

LIMITATIONS

This study might have been the first one to quantify the interrelationships among the four major joints from a dynamic strength perspective. Yet, only one angular velocity of motion was considered. This study also did not include other important joints of the body, namely, the wrist and the ankle. Not all of the shoulder and back strengths were gathered. Hence, more data may be needed to corroborate the findings.

ACKNOWLEDGMENTS

The authors wish to acknowledge Barbara Woolford, James Maida, and Mihriban Whitmore of NASA for their constructive criticisms and suggestions. Thanks to Kathleen Robinette of Wright Patterson Air Force Base for educating us on why correlation goes up when male and female data are combined. We are very grateful to all of those who worked at the Anthropometry and Biomechanics Facility at NASA-Johnson Space Center and helped us gather the strength data. Finally, we would like to acknowledge and thank the subjects who participated in this study.

REFERENCES

1. Badler, N. I., Lee, P., and Phillips, C., and Ernest M., Jack Interactive Human Model, 16th Design Automation Conference-ASME, Chicago, IL, Sept 1990.

2. Lee, P., Wei, S., Zhao, J., and Badler, N., Strength Guided Motion, 17th Annual ACM Conference on Computer Graphics and Interactive Techniques-SIGGRAPH, Dallas, TX, Aug 1990.

3. Underwood, R.C., Hilby, D.L., Holzhauser, T.B., and Tedlund, B.E., Development of the Boeing Human Model, Proceedings of the 35th Annual Meeting of the Human Factors Society, San Francisco, CA, Sept 1991.

4. Pandya, A., Maida, J., Cheang, J., and Pardue, F., Modeling Anthropometry, Strength, and Motion to Solve Space Human Factors Problems, Proceedings of the 17th Southern Biomedical Engineering Conference, San Antonio, Feb 1998.

5. Green, R. A Generic Process for Human Model Analysis, *Proceedings of the 3rd Annual Conference on Digital Human Modeling for Design and Engineering. Dearborn, MI, 2000.*

6. Schaefer, P., Rudolph, H., and Schwarz, W., Digital Man Models and Physical Strength—A New Approach in Strength Simulation, *Proceedings of the 3rd Annual Conference on Digital Human Modeling for Design and Engineering. Dearborn, MI, 2000.*

7. Ko, H., and Badler, N.I., Animating Human Locomotion with Inverse Dynamics, IEEE Computer Graphics and Applications, Vol. 16, no. 2, Mar 1996.

8. Cheang, A., Mueller, K., and Pandya, A., Validation of a Human Body Dynamics Computation Using SD/FAST, *NASA Technical Report*, Aug. 1998.

9. Praagman, M., Stokdijk, M., Veeger, H.E.J., and Visser, B., Predicting mechanical load of the gleno-humeral joint, Using Net Joint Moments, Clinical Biomechanics, Vol. 15, no. 5, 2000.

10. Vasta, P.J., Kondraske, G.V., Approach to Estimating Performance Capacity Envelopes: Knee Extensor System Example, Proceedings of the 19th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Chicago, IL, Oct 1997.

11. Schaffner, G., Dynamic Analysis of Astronaut Motions During Extravehicular Activity, *Masters Science Dissertation*, MIT, June 1995.

12. Rothaug, H., Combined Force-Posture Model for Predicting Human Postures and Motion by Using the Ramsis Human Model, *Proceedings of the 3rd Annual Conference on Digital Human Modeling for Design and Engineering. Dearborn, MI, 2000.*

13. Chaffin, D.B., Gerogi, C., Baker, G., and Nussbaum, M., Dynamic Shoulder Loads in Reaching and Material Handling Tasks, Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society, Chicago, IL, Oct 1998.

14. Hsiao, H., Guan, H., Mayeux, B., and Cutlip, R., Identifying Less Stressful Work Methods: Computer-aided Simulation vs. Human Subject Study, *Proceedings of the 3rd Annual Conference on Digital Human Modeling for Design and Engineering. Dearborn, MI, 2000.*

15. Burnett, C., and Schaff, W., Issues in using Jack Human modeling software to assess human-vehicle interaction in a driving simulator, Transportation Research Record, NRC, Washington, DC, Sept 1998.

16. Chaffin, D.B., Development of Computerized Human Static Strength Simulation Model for Job Design, Human Factors and Ergonomics in Manufacturing, Vol. 7, no. 4, Fall 1997.

17. Kroemer, K.H.E., Marras, W.S., McGlothlin, J.D., McIntyre, D.R., and Nordin, M., On the Measurement of Human Strength, International Journal of Industrial Ergonomics, vol. 6, no. 3, Nov 1990.

18. Badler, N.I., Becket, W.M., and Webber, B.L., Simulation and Analysis of Complex Human Tasks for Manufacturing, Proceedings of SPIE – The International Society for Optical Engineering, Philadelphia, PA, Oct 1995.

19 Pandya, A., Maida, J., Aldridge, A., Hassan, S., and Woolford, B., Development of an Empirically Based Biomechanical Model, SOAR Conference, TX, May 1990.